



ELSEVIER

Soil & Tillage Research 45 (1998) 39–57

**Soil &
Tillage
Research**

Long-term tillage and cropping systems affect bulk density and penetration resistance of soil cropped to dryland wheat and grain sorghum

Paul W. Unger^{*}, Ordie R. Jones

US Department of Agriculture, Agricultural Research Service, Conservation and Production Research Laboratory, P.O. Drawer 10, Bushland, TX 79012, USA

Received 2 April 1997; accepted 13 October 1997

Abstract

Stubble mulch tillage (SMT) and no-tillage (NT) are well adapted for dryland crops in the US Great Plains. Long-term use of NT, however, may impair soil physical conditions and crop yields, and, by inference, soil quality and production sustainability. We determined effects of using SMT and NT in several cropping systems for dryland winter wheat (*Triticum aestivum* L.) and grain sorghum (*Sorghum bicolor* (L.) Moench) production on soil bulk density (BD), penetration resistance (PR), and water content (WC). We determined these in 1994 in plots of a tillage method and cropping system study started in 1982 on Pullman (Torrertic Paleustoll) clay loam at Bushland, TX, USA. Due to the nature of the study, a common statistical analysis of the data was not appropriate, but eight separate analyses were possible. Besides tillage method and cropping system, these allowed comparisons due to rotation phase, land condition (level or non-level), and crop grown. Soil BD and PR always increased with depth and WC often increased. The tillage \times depth interaction effect also was significant. Soil BD and PR were lower in the tillage layer (0–10 cm depth) in SMT than in NT plots, but no definite trends for BD were evident below 10 cm. Based on regression analyses, PR with SMT was related to BD and WC of the entire profile and most depth increments. With NT, PR was related to profile BD and WC, but only to WC for individual depths. These results indicate some strength factor largely independent of BD and affected by WC strongly influences PR of NT soil. Because NT does not disturb the soil, we concluded that stable biopores created by soil organisms and root channels reduced the effects of BD differences among NT plots and that NT soils developed a rigid structure independent of BD. Reports of improved trafficability on NT soils support this conclusion. Results of this study and

^{*} Corresponding author. Tel.: +1-806-356-5738; fax: +1-806-356-5750; e-mail: pwunger@ag.gov

previously reported crop yields suggest long-term use of NT will not impair the quality and production sustainability of this and similar soils under dryland cropping conditions. Published by Elsevier Science B.V.

Keywords: Soil bulk density; Soil penetration resistance; Soil water content; Stubble mulch tillage; No-tillage; Cropping systems; Pullman clay loam; Torrertic Paleustoll

1. Introduction

A devastating drought and associated severe wind erosion plagued the US Great Plains and Canadian Prairie Provinces in the 1930s. A consequence of those conditions was the development of stubble mulch tillage (SMT), which helped control the erosion when it replaced clean tillage for dryland (non-irrigated) small grain production, primarily winter wheat (Allen and Fenster, 1986). It also is widely used for dryland grain sorghum production.

SMT usually retains adequate crop residues on the soil surface to control wind and water erosion. It also improves water conservation (McCalla and Army, 1961), which is highly important for dryland crop production in regions such as the semi-arid southern Great Plains. Erosion control and water conservation improve with increasing amounts of crop residues retained on the surface (McCalla and Army, 1961; Greb et al., 1967, 1970; Unger, 1978, 1984a; Unger and Wiese, 1979), but residue production by dryland crops often is limited. Producers in the region are adopting reduced tillage and no-tillage (NT) production methods that retain more residues on the surface. Use of these methods led to greater water conservation, which, along with such factors as improved weed control, cultivars, and fertilizer practices, resulted in a shift away from the widely-used wheat–fallow cropping system (one crop in 2 yr). That system has been replaced by a wheat–fallow–sorghum–fallow (designated WSF) system (two crops in 3 yr) or even annual (continuous) cropping (one crop each year) of wheat or grain sorghum.

Grain yields of dryland wheat and grain sorghum in the US Great Plains with NT generally equal or exceed those with SMT (Jones and Popham, 1997; Norwood, 1992, 1994; Unger, 1994). Also, relatively short-term use of NT has not adversely affected soil physical conditions (Unger, 1984b; Unger and Fulton, 1990). There is concern, however, whether long-term use of reduced tillage or NT will result in soil physical conditions that impair crop yields (Hill and Cruse, 1985; Hammel, 1989; Grant and Lafond, 1993; Steyn et al., 1995) and, by inference, soil quality and crop production sustainability. Widespread interest in soil quality and production sustainability makes it imperative that effects of widely used tillage and cropping practices on soil physical conditions be thoroughly understood.

For a study initiated in 1982, Jones and Popham (1997) found no significant differences in average wheat and grain sorghum yields due to tillage method (SMT or NT) used in any cropping system and there were no yield trends during the study, suggesting that soil physical conditions were not affected by the tillage methods. This study of > 10 yr, however, allowed us to evaluate effects of using SMT and NT in several cropping systems on some soil physical conditions. Our objective was to

determine effects of tillage methods and cropping systems used for dryland winter wheat and grain sorghum production on soil bulk density (BD) and penetration resistance (PR). We also determined soil water content (WC) to aid interpretation of the PR data.

2. Materials and methods

A field study, established in 1982 on Pullman clay loam (fine, mixed, thermic Torrtic Paleustoll) at the USDA Conservation and Production Research Laboratory, Bushland, TX, USA, involved SMT and NT in several dryland grain sorghum and winter wheat cropping systems. The plots were either level (end-to-end and side-to-side) or non-level (on the contour). Soil slope before levelling ranged from 0.5 to 1.5%, depending on location in the field. Plots were 9 by 160 m and farmed with commercially-available equipment. Berms prevented water from flowing onto or off level plots. Run-off was possible from one end of non-level plots. The study had a randomized complete block design with three replications.

Sufficient plots were used so that each phase of all systems was in place each year. Soil physical conditions were evaluated in 1994, about 12 yr after initiating the study.

The cropping systems evaluated are given in Table 1. In SMT plots, we used a Richardson¹ sweep plow with one 1.5- and two 1.8-m-wide blades to control weeds and prepare seedbeds. Tillage was 7–10 cm deep. We applied herbicides at recommended rates for additional weed control in SMT plots and for all weed control in NT plots (Jones and Popham, 1997).

We seeded winter wheat ‘TAM 107’ in 0.30-m spaced rows with a high-clearance drill equipped with hoe openers and press wheels, and DeKalb grain sorghum hybrid ‘DK42y’ in 0.75-m spaced rows with a six-row John Deere Max-Emerge planter. Because a plant nitrogen deficiency was noted in 1987, 40 to 45 kg ha⁻¹ N, as ammonium nitrate, was broadcast before planting wheat and sorghum in subplots starting in 1988. Precipitation, measured at the plots, averaged 520 mm from 1984 through 1993 (Jones and Popham, 1997). In 1994, it totalled 10 mm before we determined BD in May and 258 mm before we measured PR in July.

We obtained two cores from each fertilizer subplot with a tractor-mounted sampler to determine soil BD. The cores were 54 mm in diameter, partitioned into 0–4, 4–10, 10–20, 20–35, 35–50, and 50–65 cm segments, weighed, oven-dried, and re-weighed before calculating BD.

We measured soil PR at 10 sites in each subplot to a 50-cm depth with a hand-held recording penetrometer (Bush Soil Penetrometer SP10, Findlay Irvine, Penicuik, UK) that had a 30° cone with a 12.8-mm diameter base. To determine WC effects on PR, we averaged the PR values by 10-cm depth increments, which corresponded to depths used

¹ The mention of trade or manufacturer names is made for information only and does not imply an endorsement, recommendation, or exclusion by the USDA-Agricultural Research Service. Mention of a pesticide does not constitute a recommendation for use nor does it imply registration under FIFRA as amended.

Table 1
Cropping systems evaluated

System ^a	Land condition	Tillage ^a	Crops	Crop frequency
WSF	Level/non-level	SMT/NT	Wheat/sorghum	Two crops 3 yr ⁻¹
CW	Level/non-level	SMT/NT	Wheat	One crop yr ⁻¹
WF	Level/non-level	SMT/NT	Wheat	One crop 2 yr ⁻¹
CS	Level/non-level	SMT/NT	Sorghum	One crop yr ⁻¹

^aAbbreviations are: WSF, wheat–sorghum–fallow; CW, continuous wheat; WF, wheat–fallow; CS, continuous sorghum; SMT, stubble mulch tillage; NT, no-tillage.

for WC determinations. We determined water contents by core sampling when we determined PR.

Data were analyzed by the analysis of variance technique (Statistical Analysis Systems, 1989). Because preliminary analyses showed fertilizer treatments did not affect soil BD or PR, we averaged data for fertilizer subplots before further analyzing the data. Although all treatments were included in a common study, involving data for all treatments in common statistical analyses was not appropriate. Therefore, we separately analyzed data for those treatments where effects of cropping systems, tillage methods, rotation phases, land conditions (level and non-level), and crops could be compared. This allowed eight comparisons (CPs) of the data, which were:

- CP-1—cropping system (WSF, CW, WF) and tillage method (SMT, NT) effects on level plots cropped to wheat;
- CP-2—cropping system (WSF, CS) and tillage method (SMT, NT) effects on level plots cropped to grain sorghum;
- CP-3—cropping system (WSF, WF) and tillage method (SMT, NT) effects on level plots in fallow;
- CP-4—rotation phase (wheat, sorghum, fallow) and tillage method (SMT, NT) effects on level WSF plots;
- CP-5—land condition (level, non-level) and rotation phase (wheat, sorghum, fallow) effects on WSF plots with SMT;
- CP-6—land condition (level, non-level) and rotation phase (wheat, fallow) effects on WF plots with SMT;
- CP-7—land condition (level, non-level) and crop (wheat, sorghum) effects on continuous cropping plots with SMT; and
- CP-8—crop (wheat, sorghum) and tillage method (SMT, NT) effects on level continuous cropping plots.

When significant at the $P \leq 0.05$ level of probability, we separated the means using the protected least significant difference (Prot. LSD) procedure.

We used multiple regression analyses to determine effects of soil WC and BD on PR. For these analyses, we used actual, squared, and cubed WC and BD values in the STEPWISE (backwards) procedure of SAS (Statistical Analysis Systems, 1989). Because we determined BDs at depth increments different from those at which we determined PR and WC, we used a weighting procedure to calculate BDs for depths that corresponded to those for PR and WC.

3. Results and discussion

3.1. Soil bulk density (BD)

Soil BD for all comparisons averaged 1.49, 1.44, 1.48, 1.63, 1.67, and 1.73 Mg m^{-3} at the 0–4, 4–10, 10–20, 20–35, 35–50, and 50–65 cm depths, respectively. The mean LSD for depth was 0.07 Mg m^{-3} . The mean LSD is not from an analysis of the combined data, but it suggests BDs for the three upper increments were similar and that they were less than for the lower increments. Had it been possible to combine all data in a common analysis, more degrees of freedom would have been involved, which undoubtedly would have resulted in a lower LSD value. An increase in BD with depth is typical for Pullman soil (Unger and Pringle, 1981).

The only direct effect of tillage on BD occurred in level fallow plots for which the mean was lower with SMT than with NT (1.60 vs. 1.64 Mg m^{-3}). This difference resulted mainly from the difference at 4–10 cm, where use of SMT had loosened the soil.

For sorghum in level plots, mean BD was greater for the CS than the WSF cropping system (1.64 vs. 1.60 Mg m^{-3}). Mean BD differences due to rotation phase in level WSF plots were not significant, but the mean was less for CW than for CS (1.58 vs. 1.61 Mg m^{-3}) in continuous cropping plots with SMT and for the CW than the CS system (1.57 vs. 1.64 Mg m^{-3}) in level continuous cropping plots. These results suggest

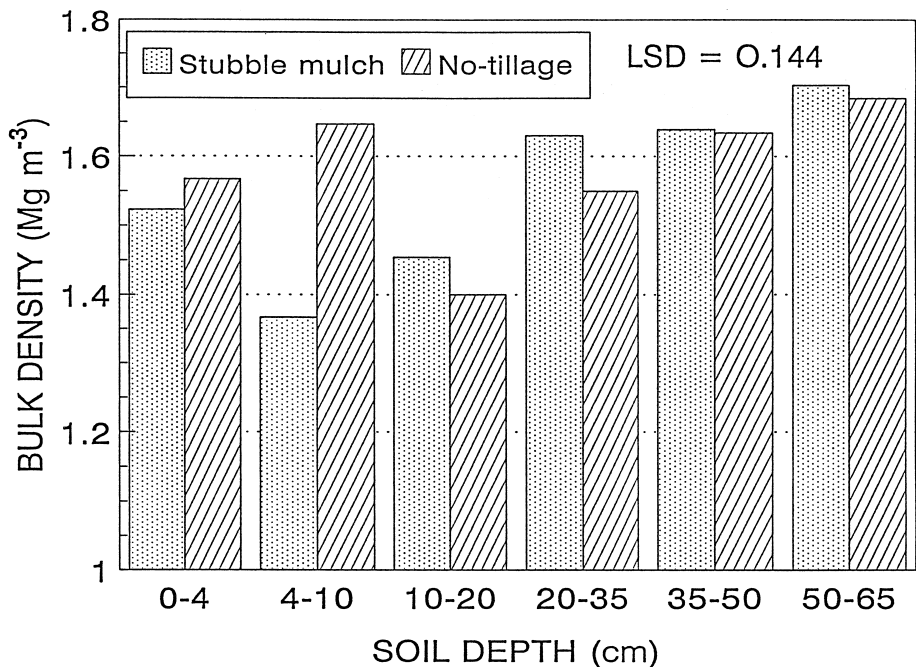


Fig. 1. Soil bulk density (average for cropping systems) in level wheat plots (CP-1 comparison) with stubble mulch and no-tillage, Bushland, TX.

wheat in the WSF rotation had a carryover effect on BD when the plots later were used for grain sorghum, thus resulting in the lower BD than with the CS system.

Whereas tillage affected mean BD only on level fallow plots, the depth \times tillage interaction always affected BD. The interactions were significant because BD was greater with NT than with SMT at 4–10 cm where use of SMT had loosened the soil, but it remained unloosened in NT plots. The results were similar for other comparisons. Results shown in Fig. 1 for level wheat plots are typical for rotation plots in wheat, sorghum, or fallow while those in Fig. 2 are for level continuous cropping plots. The BDs for the two conditions are similar, except that the difference due to tillage was greater at 4–10 cm in level wheat (Fig. 1) than in level continuous cropping plots (Fig. 2), BDs were relatively low at 10–20 cm in level wheat plots (Fig. 1), and BD at 0–4 cm tended to be greater with NT in level continuous cropping plots (Fig. 2).

The only other significant two-way interaction for BD was for depth \times land condition (level vs. non-level) in continuous cropping plots with SMT for which BD at 0–4 cm was less in level than in non-level plots (1.41 vs. 1.55 Mg m^{-3}). This difference possibly resulted from water flow across the surface in non-level plots, which caused greater dispersion and rearrangement of surface soil particles and, therefore, the greater BD.

The depth \times cropping system \times tillage interaction affected BD in level sorghum and fallow plots. The BD at 0–4 cm in sorghum plots was lowest with NT for the WSF system and not different for other cropping system–tillage method combination treat-

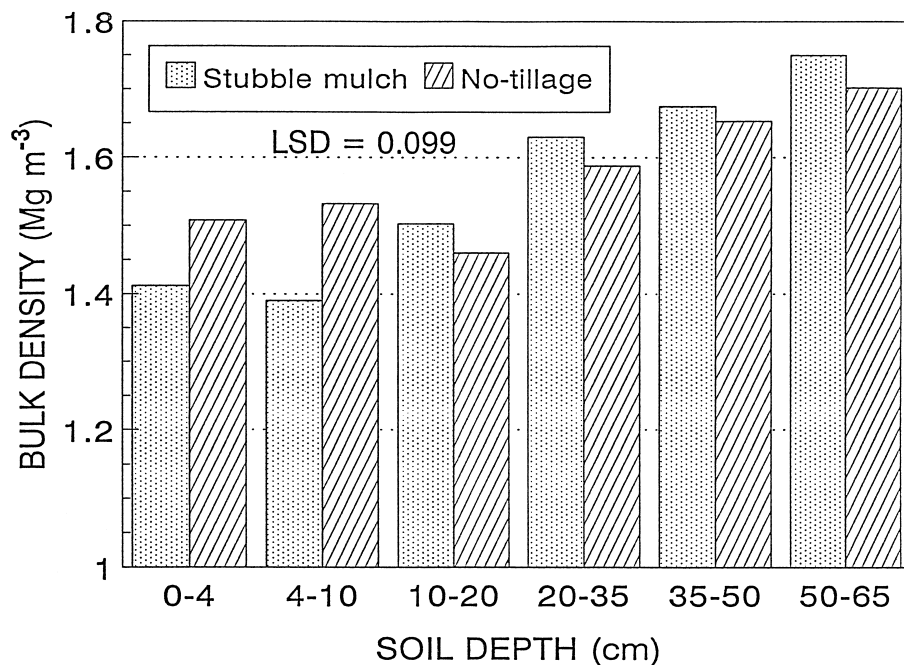


Fig. 2. Soil bulk density (average for crops) in level continuous cropping plots (CP-8 comparison) with stubble mulch and no-tillage, Bushland, TX.

Table 2

Soil bulk densities (Mg m^{-3}) in level wheat, sorghum, and fallow plots as affected by cropping system, tillage practice, and sampling depth, Bushland, TX

System	Tillage	Sampling depth (cm)						Weighted means	
		0–4	4–10	10–20	20–35	35–50	50–65	System	System-tillage
<i>Wheat plots (CP-1 comparison)</i>									
WSF	SMT	1.56	1.35	1.47	1.64	1.59	1.71	1.60	1.59
	NT	1.49	1.74	1.40	1.62	1.68	1.67		1.62
CW	SMT	1.39	1.31	1.45	1.60	1.65	1.72	1.57	1.58
	NT	1.52	1.56	1.39	1.52	1.64	1.68		1.57
WF	SMT	1.63	1.44	1.44	1.65	1.67	1.68	1.59	1.61
	NT	1.69	1.64	1.40	1.51	1.58	1.71		1.58
Depth mean		1.55	1.51	1.43	1.59	1.64	1.69		
Tillage means: SMT = 1.55; NT = 1.58									
LSD ^a (0.05 level): Depth (<i>D</i>) = 0.09; System (<i>S</i>) = NS ^b ; Tillage (<i>T</i>) = NS; <i>D</i> × <i>S</i> = NS; <i>D</i> × <i>T</i> = 0.11; <i>S</i> × <i>T</i> = NS; <i>D</i> × <i>S</i> × <i>T</i> = NS									
<i>Sorghum plots (CP-2 comparison)</i>									
WSF	SMT	1.48	1.33	1.47	1.62	1.66	1.73	1.60	1.60
	NT	1.29	1.64	1.50	1.61	1.66	1.71		1.61
CS	SMT	1.44	1.47	1.56	1.66	1.67	1.78	1.64	1.64
	NT	1.50	1.51	1.53	1.66	1.66	1.72		1.63
Depth mean		1.43	1.49	1.51	1.64	1.67	1.74		
Tillage means: SMT = 1.57; NT = 1.58									
LSD (0.05 level): Depth (<i>D</i>) = 0.10; System (<i>S</i>) = 0.02; Tillage (<i>T</i>) = NS; <i>D</i> × <i>S</i> = NS; <i>D</i> × <i>T</i> = 0.10; <i>S</i> × <i>T</i> = NS; <i>D</i> × <i>S</i> × <i>T</i> = 0.14									
<i>Fallow plots (CP-3 comparison)</i>									
WSF	SMT	1.40	1.35	1.43	1.67	1.69	1.80	1.62	1.62
	NT	1.45	1.47	1.47	1.62	1.69	1.72		1.61
WF	SMT	1.59	1.26	1.51	1.67	1.72	1.76	1.65	1.64
	NT	1.52	1.64	1.53	1.64	1.72	1.73		1.65
Depth mean		1.49	1.43	1.49	1.65	1.70	1.75		
Tillage means: SMT-1.57; NT-1.60									
LSD (0.05 level): Depth (<i>D</i>) = 0.09; System (<i>S</i>) = NS; Tillage (<i>T</i>) = 0.02; <i>D</i> × <i>S</i> = NS; <i>D</i> × <i>T</i> = 0.05; <i>S</i> × <i>T</i> = NS; <i>D</i> × <i>S</i> × <i>T</i> = 0.08									

^aLeast significant difference.

^bNot significant.

ments (Table 2). At 4–10 cm, BD was lower with SMT for the WSF system than for other treatments and higher with NT for the WSF system than for SMT in either cropping system. The BDs were similar for a given depth below 10 cm for all treatments.

The three upper and the lowest depth increments contributed to the three-way interaction effect on BD in fallow plots (Table 2). Loosening the soil by tillage lowered the BD at 4–10 cm, but had no consistent effect at 0–4 or 10–20 cm. The reason for the greater BD with SMT than with NT at 50–65 cm in WSF plots is not apparent.

3.2. Penetration resistance (PR) and water content (WC)

Soil mean PRs for all comparisons were 0.72, 1.30, 1.87, 2.36, and 2.91 MPa for the 0–10, 10–20, 20–30, 30–40, and 40–50 cm depths, respectively. The mean LSD for

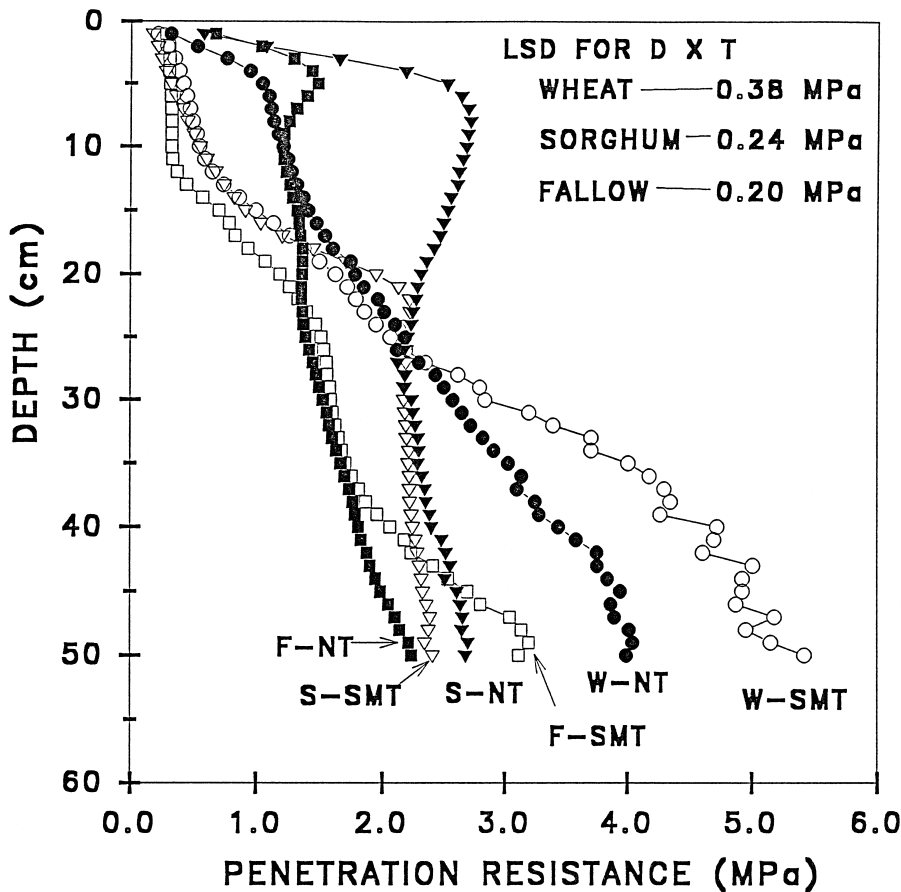


Fig. 3. Soil penetration resistances due to stubble mulch tillage (SMT) and no-tillage (NT) in wheat (W), sorghum (S), and fallow (F) plots of the wheat–sorghum–fallow cropping system (CP-1, CP-2, and CP-3 comparisons), Bushland, TX. The least significant differences (LSDs) for the tillage \times depth interactions are based on statistical analyses involving data for 1, 5, 10, 20, 30, 40, and 50 cm depths.

depth was 0.30 MPa, a value exceeded for each successive increment. The mean LSD for PR, as for BD, is not based on a common statistical analysis, but it suggests all differences due to depth were significant.

The PRs illustrated in Fig. 3 for level wheat, sorghum, and fallow plots of the WSF system are typical for comparisons involving tillage. We used PRs at 1, 5, 10, 20, 30, 40, and 50 cm to analyze the data separately for each rotation phase. Differences at 1 cm were significant in sorghum and fallow plots. In all phases, PR was greater with NT at 5 and 10 cm. Below 10 cm, differences due to tillage methods were slight in sorghum and fallow plots, but PR was greater with SMT in wheat plots below 30 cm. This greater PR is attributed to the lower WC in SMT plots.

Lower PR due to SMT in the upper 15–20 cm of profiles resulted mainly from soil loosening by tillage. The NT plots were not loosened. Because SMT loosened soil only to about 10 cm, the reason for a major difference to about 20 cm in sorghum plots is not clear. At 10–20 cm, BDs were identical due to tillage, but WC was greater in NT plots. These results suggest SMT loosened the soil to more than 10 cm at some time during the study and the PRs reflect that deeper loosening. Plant root penetration differences possibly were involved also.

For level wheat plots, mean PR differed due to cropping system, being lower for CW (1.79 MPa) than for WF (2.32 MPa) or WSF (2.42 MPa). The reason for the difference is not apparent because wheat was harvested from all plots about 30 days before measuring PR and soil WC differences were not significant.

The mean PR in level fallow plots differed due to cropping system, being 1.47 MPa in WSF and 1.29 MPa in WF plots. Soil WCs for this comparison were different also. The PR differences, therefore, reflected the WC changes that occurred since harvest of the previous crop. The mean WC was greater in WF plots ($0.431 \text{ mm}^3 \text{ mm}^{-3}$) in fallow since wheat harvest 13 months earlier than in WSF plots ($0.405 \text{ mm}^3 \text{ mm}^{-3}$) in fallow since sorghum harvest about 8 months earlier. (We discuss soil PR and WC relationships in more detail later in this section).

Land condition (level or non-level) affected PRs in WF and continuous cropping (wheat or sorghum) plots, both with SMT. For the WF rotation, mean PR was 1.79 MPa in level and 1.43 MPa in non-level plots. The WC was greater in non-level than level plots (0.359 vs. $0.265 \text{ mm}^3 \text{ mm}^{-3}$), showing an inverse relationship between PR and WC for this comparison. A possible reason for the greater WC in non-level plots is that run-off limited soil water for plant growth and root development at some critical stage, thus limiting water use from deeper in the profile later in the growing season.

Whereas PR was greater in level than in non-level WF plots with SMT, the results were opposite in continuous cropping (CW and CS) plots with SMT. Mean PRs were 1.84 and 2.11 MPa in level and non-level plots, respectively, for these systems. Though not significant, WC tended to be greater in non-level than in level plots (0.203 vs. $0.146 \text{ mm}^3 \text{ mm}^{-3}$), a trend similar to results obtained for the WF plots with SMT above.

Mean PR was greater with NT than with SMT in level sorghum (2.02 vs. 1.74 MPa), level fallow (1.45 vs. 1.31 MPa), and level WSF rotation (2.07 vs. 1.86 MPa) plots. The WCs also differed, being greater with NT. Whereas WC affected mean PR (lower PR and greater WC in level fallow plots than in level sorghum or level WSF rotation plots), effects of NT per se overshadowed the apparent advantage of greater WCs with respect

to reducing soil PR. Mean PRs resulting from tillage were not great enough to prevent plant root penetration (Taylor and Gardner, 1963), but they could limit root development (Hammel, 1989). The greater PRs with NT apparently have not affected crop yields. Wheat and sorghum yields with NT have equalled or exceeded those with SMT on Pullman soil (Unger, 1994; Jones and Popham, 1997). Also, using NT has not impaired growth and soil water uptake by roots, apparently because Pullman soil shrinks when water is extracted, which allows root penetration and water use at greater depths.

Mean PR in level WSF rotation plots was greatest (2.42 MPa) in wheat, intermediate (2.00 MPa) in sorghum, and lowest (1.47 MPa) in fallow plots. This trend was opposite the trend for WC (0.214 mm³ mm⁻³ in wheat, 0.245 in sorghum (not different from wheat), and 0.405 in fallow plots). For the WSF rotation with SMT, mean PRs were 2.35 MPa in wheat (harvested 1 month earlier), 1.83 MPa in sorghum (planted 1 month earlier), and 1.35 MPa in fallow (sorghum harvested 8 months earlier) plots. For this comparison, WC was greater in fallow (0.419 mm³ mm⁻³) than in wheat (0.224 mm³ mm⁻³) and sorghum (0.218 mm³ mm⁻³) plots. Results for comparisons in WSF plots show at least a partial effect of soil WC on PR. We noted a definite inverse relationship between WC and PR in WF plots with SMT (PRs were 1.91 MPa in wheat and 1.32 MPa in fallow plots; associated WCs were 0.231 and 0.392 mm³ mm⁻³). The WC differences and resultant PR differences are attributed to the time since harvest of the

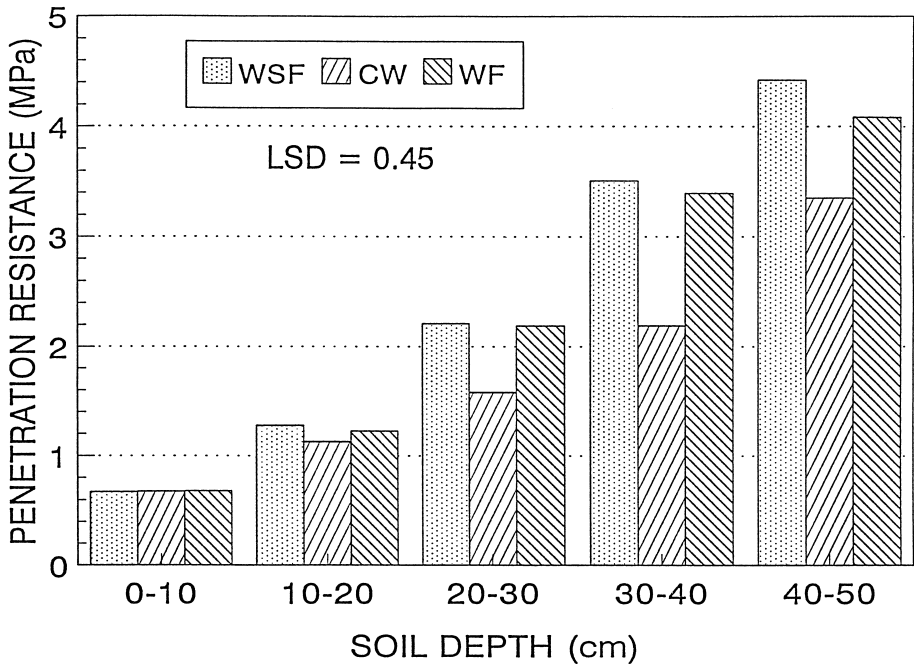


Fig. 4. Soil penetration resistance (average for tillage methods) in level wheat plots (CP-1 comparison), Bushland, TX. Cropping systems are: WSF, wheat–sorghum–fallow; CW, continuous wheat; WF, wheat–fallow.

last crop, which affected the soil water content. Wheat was harvested from wheat plots about 1 month before and from fallow plots about 13 months before we measured PR.

For continuous cropping with SMT, mean PR was lower in CW than in CS plots (1.73 vs. 2.23 MPa). Mean WC, however, also was lower in CW than in CS plots (0.137 vs. 0.212 mm³ mm⁻³), a trend different than expected based on most results discussed above. The reason for this reversal of trends is not apparent.

The depth \times cropping system interaction affected PR in level wheat and fallow plots. In wheat plots (Fig. 4), PRs due to cropping systems were similar at 0–10 and 10–20 cm depths, but lower in CW than in WSF or WF plots below 20 cm. Because WCs for a given depth were similar, the reason for the PR differences is not apparent. For level fallow plots, the interaction effect resulted from similar PRs due to cropping systems to 40 cm and greater PR in WSF than in WF plots (2.38 vs. 1.84 MPa) at 40–50 cm. Again, the WCs were similar and the reason for the PR results is not apparent.

The depth \times rotation phase interaction affected PR and WC in level WSF plots, WSF plots with SMT, and WF plots with SMT. In level WSF plots (Fig. 5), PR was greater near the surface (0–20 cm) in sorghum plots from which the crop had used much of the soil water at the time of measurement (Fig. 6). In contrast, rain provided some water to the near-surface soil in wheat plots. Trends were reversed deeper in the profile where wheat plots had a low WC and high PR, and sorghum and fallow plots had relatively high WCs and low PRs. In WSF plots with SMT, PR and WC trends were similar to

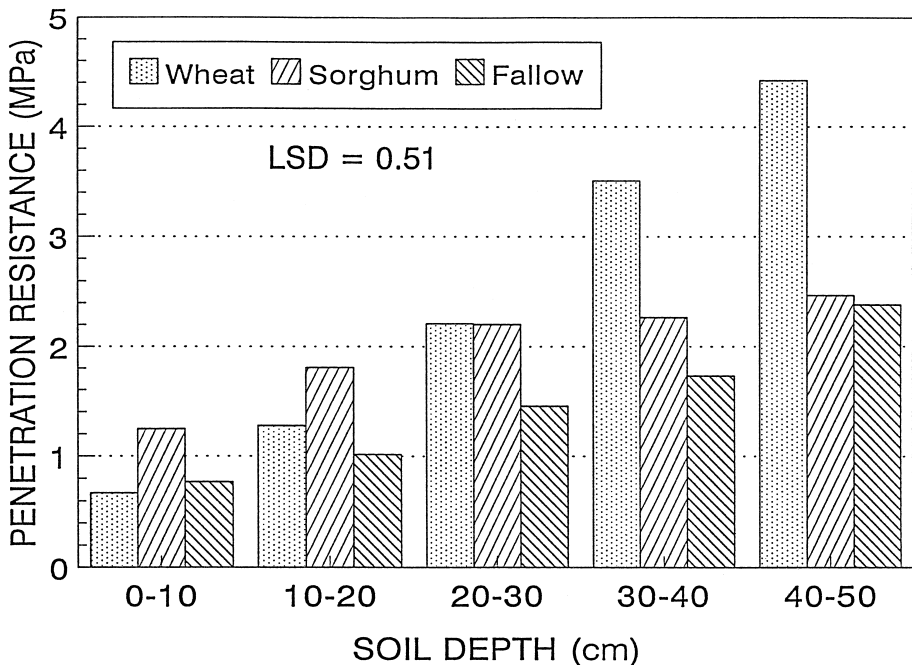


Fig. 5. Soil penetration resistance (average for tillage methods) in level wheat–sorghum–fallow rotation plots (CP-4 comparison), Bushland, TX.

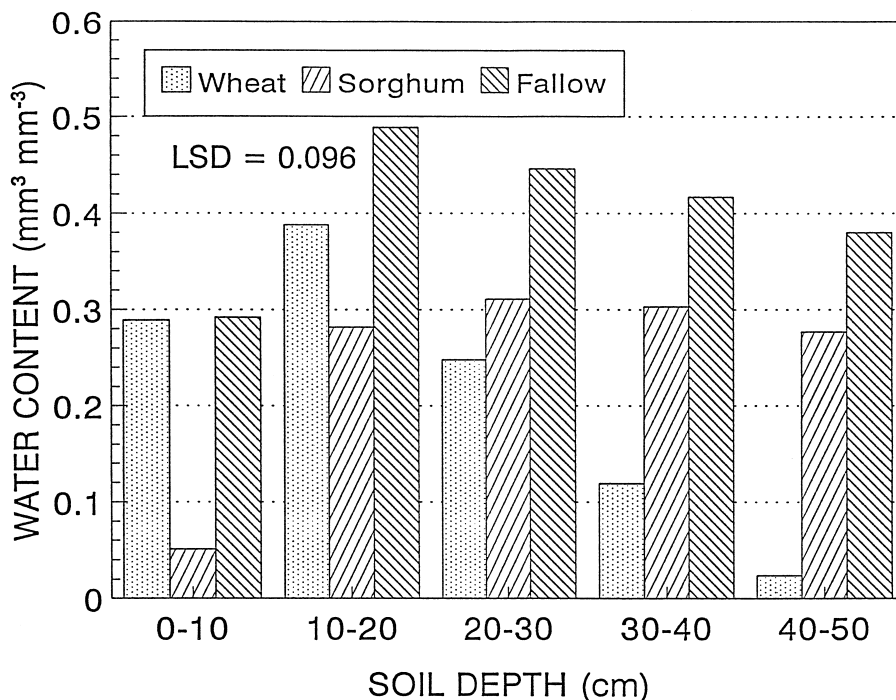


Fig. 6. Soil water content (average for tillage methods) in level wheat–sorghum–fallow rotation plots (CP-4 comparison), Bushland, TX.

those shown in Figs. 5 and 6, with the reasons the same as for the level WSF plots. In WF plots with SMT, PRs were similar for wheat and fallow plots at 0–10 and 10–20 cm (data not shown). The WCs also were similar for at 0–10 cm, but greater below 10 cm in fallow plots because of more water storage since harvest of the previous crop. Overall, PR and WC results for WF plots with SMT were similar to those illustrated for level WSF plots in Figs. 5 and 6.

The depth \times land condition interaction affected PR in WF plots with SMT. At 30–40 and 40–50 cm, PRs were greater in level plots. Although the interaction effect on WC was not significant, WC tended to be lower in level plots at those depths and, therefore, influenced the PRs. The WC differences due to land condition (level or non-level) probably resulted from run-off and crop growth differences, as mentioned previously.

The depth \times crop interaction affected PR and WC in continuous cropping plots with SMT and level continuous cropping plots. In both cases, WCs were greater in wheat than sorghum plots at 0–10 cm (rain provided some water to wheat plots whereas growing sorghum had extracted some water), similar at 10–20 and 20–30 cm, and lower in wheat than sorghum plots at 30–40 and 40–50 cm (data not shown). Although WCs due to crops were similar for the two comparisons, the PRs differed markedly. For continuous cropping with SMT, PR due to crops was similar at 0–10 cm, greater in sorghum than wheat plots at 10–20 and 20–30 cm, and similar below 30 cm (although

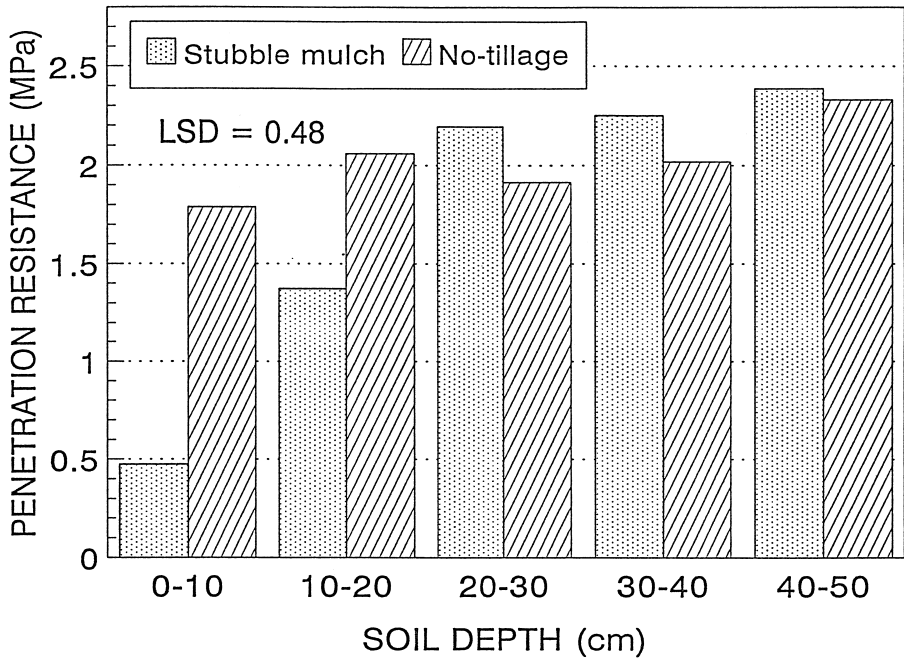


Fig. 7. Soil penetration resistance (average for cropping systems) in level sorghum plots (CP-2 comparison) with stubble mulch tillage and no-tillage, Bushland, TX.

WC was much lower in wheat plots). In level continuous cropping plots, PR was greater in sorghum plots at 0–10 cm, similar for both crops at 10–20 cm, and greater in wheat than sorghum plots below 20 cm. The PRs for level continuous cropping plots followed expected trends, based on soil WCs. The differing trends for the two comparisons may be related to the overall WC differences. Mean WCs were $0.174 \text{ mm}^3 \text{ mm}^{-3}$ in continuous cropping plots with SMT and $0.222 \text{ mm}^3 \text{ mm}^{-3}$ in level continuous cropping plots.

The depth \times tillage method interaction always affected PR, but affected WC only in level sorghum plots. Even for this comparison, however, trends for PR (Fig. 7) seem not closely related (inversely) to soil WC (Fig. 8). The PR was or tended to be greater with NT than with SMT at 0–10 and 10–20 cm and little affected by tillage at greater depths, although soil WCs differed appreciably. At prevailing WCs, PRs with SMT and NT were in the range that limits root growth (Taylor and Gardner, 1963), but favorable yields were obtained with both methods (Jones and Popham, 1997).

The cropping system \times tillage method interaction affected PR, but not WC, in level sorghum plots. For this comparison, PR was greater with NT than with SMT (2.36 vs. 1.64 MPa) in WSF plots, but not different in CS plots (1.69 vs. 1.83 MPa). The WCs were greater with NT in both cases, namely, 0.269 and $0.306 \text{ mm}^3 \text{ mm}^{-3}$ with NT vs. 0.221 and $0.211 \text{ mm}^3 \text{ mm}^{-3}$ with SMT in WSF and CS system plots, respectively.

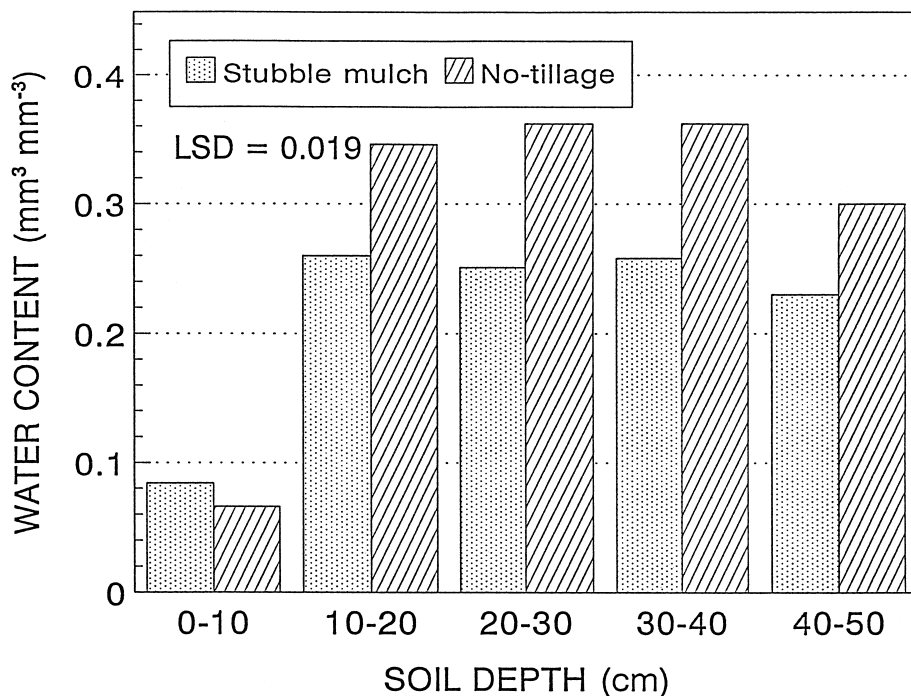


Fig. 8. Soil water content (average for cropping systems) in level sorghum plots (CP-2 comparison) with stubble mulch tillage and no-tillage, Bushland, TX.

The rotation phase \times tillage interaction affected PR in level WSF plots. In sorghum plots, mean PRs were 1.64 MPa with SMT and 2.36 MPa with NT. The PRs due to SMT and NT within other phases were similar, being 2.53 and 2.30 MPa, respectively, in wheat plots and 1.40 and 1.54 MPa, respectively, in fallow plots. The PRs in wheat and fallow plots did not differ from those with NT and SMT, respectively, in sorghum plots. The low PRs in fallow plots were associated with high WCs (0.401 and 0.408 $\text{mm}^3 \text{mm}^{-3}$), but WC and PR were higher with NT (0.269 $\text{mm}^3 \text{mm}^{-3}$ and 2.36 MPa) than with SMT (0.221 $\text{mm}^3 \text{mm}^{-3}$ and 1.64 MPa) in sorghum plots, showing that NT in sorghum affects PR at least partially independent of soil WC. In wheat plots, PRs were inversely related to WCs, which were 0.167 and 0.261 $\text{mm}^3 \text{mm}^{-3}$ with SMT and NT, respectively.

The land condition \times rotation phase interaction affected PR and WC in WF plots with SMT. Mean PRs were 2.37 and 1.22 MPa in level wheat and fallow plots, respectively, and 1.45 and 1.41 MPa in non-level wheat and fallow plots, respectively. Corresponding WCs were 0.139 and 0.390 $\text{mm}^3 \text{mm}^{-3}$ in level plots and 0.324 and 0.393 $\text{mm}^3 \text{mm}^{-3}$ in non-level plots, showing a relatively close inverse relationship between PR and WC for this comparison.

The land condition \times crop interaction affected PR and WC in continuous cropping plots with SMT. Mean PRs were 1.85 and 1.83 MPa in level wheat and sorghum plots, respectively, and 1.60 and 2.63 MPa in non-level wheat and sorghum plots, respectively.

Table 3

Soil penetration resistance (MPa) and water content ($\text{mm}^3 \text{mm}^{-3}$) of wheat–fallow plots with stubble mulch tillage as affected by land condition (level or non-level), rotation phase, and sampling depth (CP-6 comparison), Bushland, TX

Land condition	Phase	Sampling depth (cm)					Means	
		0–10	10–20	20–30	30–40	40–50	Land condition	Land condition-phase
<i>Penetration resistance (PR)</i>								
Level	Wheat	0.42	1.08	2.34	3.60	4.39	1.79	2.37
	Fallow	0.37	0.82	1.36	1.62	1.93		1.22
Non-level	Wheat	0.21	0.92	1.63	2.02	2.45	1.43	1.45
	Fallow	0.19	0.98	1.67	1.89	2.34		1.41
Depth mean		0.30	0.95	1.75	2.28	2.78		
Phase means: Wheat = 1.91; Fallow = 1.32								
LSD ^a (0.05 level): Depth (<i>D</i>) = 0.25; Land condition (<i>L</i>) = 0.14; Phase (<i>P</i>) = 0.16; $D \times L = 0.31$; $D \times P = 0.35$; $L \times P = 0.22$; $D \times L \times P = 0.50$								
<i>Water content (WC)</i>								
Level	Wheat	0.275	0.246	0.107	0.047	0.019	0.265	0.139
	Fallow	0.248	0.469	0.420	0.438	0.375		0.390
Non-level	Wheat	0.291	0.372	0.365	0.269	0.322	0.359	0.324
	Fallow	0.293	0.439	0.410	0.428	0.395		0.393
Depth mean		0.278	0.382	0.326	0.296	0.278		
Phase means: Wheat = 0.231; Fallow = 0.392								
LSD (0.05 level): Depth (<i>D</i>) = NS ^b ; Land condition (<i>L</i>) = 0.058; Phase (<i>P</i>) = 0.039; $D \times L = \text{NS}$; $D \times P = 0.087$; $L \times P = 0.055$; $D \times L \times P = \text{NS}$								

^aLeast significant difference.

^bNot significant.

The latter mean was greater than the other means. Mean WCs were 0.080 and 0.212 $\text{mm}^3 \text{mm}^{-3}$ in level wheat and sorghum plots, respectively, and 0.195 and 0.211 $\text{mm}^3 \text{mm}^{-3}$ in non-level wheat and sorghum plots, respectively, with the first mean being lower than the other means. Mean PRs were not closely related to mean WCs, apparently due to differences in water distribution in the profile as discussed previously regarding the depth \times crop interaction.

The depth \times land condition \times rotation phase interaction for WF plots with SMT was the only three-way interaction that affected PR. The PRs within either the 0–10 or 10–20 cm depth increments were similar, but differed for all other increments (Table 3). The PR was greatest in level wheat plots at all depths greater than 20 cm. At 40–50 cm, PR in non-level wheat plots also was greater than in level fallow plots. Although the three-way interaction for WC was not significant, the PRs were closely related (inversely) to the WCs (Table 3). This was especially the case in level plots for which low WCs with wheat resulted in high PRs. Low WCs at depths greater than 20 cm resulted from water use by the previous crop (harvested about 1 month earlier).

Most WC differences were discussed along with the PR differences, and will not be further discussed. Some WCs differed, however, although PRs for the comparisons were similar. In level wheat plots involving the WSF system, mean WCs were 0.128 and 0.269 $\text{mm}^3 \text{mm}^{-3}$ with SMT and NT, respectively. In level continuous cropping plots, mean WCs were 0.146 and 0.298 $\text{mm}^3 \text{mm}^{-3}$ with SMT and NT, respectively, with the difference being greater in wheat than in sorghum plots. The WCs with SMT and NT were 0.079 and 0.290 $\text{mm}^3 \text{mm}^{-3}$, respectively, in wheat plots, and 0.212 and 0.306 $\text{mm}^3 \text{mm}^{-3}$, respectively, in sorghum plots, showing the major advantage of NT over SMT regarding soil water storage from rainfall.

Crops per se also affected WCs in level continuous cropping plots. The mean WC was greater in CS than in CW plots (0.259 vs. 0.185 $\text{mm}^3 \text{mm}^{-3}$). This is logical because sorghum was planted about 1 month earlier on land where the previous harvest was about 8 months before sampling whereas harvest was about 1 month before sampling on wheat plots.

In WSF plots with SMT, mean WC was greater in non-level than in level plots (0.311 vs. 0.263 $\text{mm}^3 \text{mm}^{-3}$), probably because run-off from non-level plots resulted in limited soil water near the surface at some critical plant growth stage. This could have hampered root penetration, thus limiting soil water use as compared with that in level plots. The land condition \times rotation phase interaction for WSF plots with SMT affected WC. The WC was lower in level than in non-level wheat plots (0.167 vs. 0.280 $\text{mm}^3 \text{mm}^{-3}$), apparently for the reason given above. In sorghum plots (planted about 1 month earlier after 10–11 months of fallow), WCs were similar for both land conditions (0.221 vs. 0.214 $\text{mm}^3 \text{mm}^{-3}$ in level and non-level plots, respectively). The WCs were similar also in fallow plots (8 months after sorghum harvest), namely, 0.401 and 0.437 $\text{mm}^3 \text{mm}^{-3}$ in level and non-level plots, respectively. Similar results for sorghum and fallow plots (both after major fallow periods) and differences for wheat plots due to land condition support the reasoning that run-off from non-level plots results in a water deficit at a critical growth stage, which limits plant root development and water use from deeper in the profile. The WCs are similar initially after fallow, but crop water use is less in non-level than in level plots, as we found in wheat plots.

Table 4

Relationships^a among soil penetration resistance (PR), water content (WC), and bulk density (BD) as affected by soil depths and tillage methods used for dryland winter wheat and grain sorghum production, Bushland, TX

Depth (cm)	Tillage ^b	Term ^c	Equation	R^2 ^d	Significance ^e
<i>Combined by depth and tillage</i>					
0–50	All	1	$PR = -5.77 - 3.36WC + 5.44BD$	0.534	0.0001
<i>Combined by depth</i>					
0–50	SMT	1	$PR = -8.57 - 4.02WC + 7.22BD$	0.689	0.0001
	NT	1	$PR = 3.00 - 3.42WC$	0.365	0.0001
		1,2	$PR = 1.11 - 3.42WC + 0.75BD^2$	0.438	0.0001
<i>For individual depths</i>					
0–10	NT	1	$PR = 2.02 - 3.48WC$	0.869	0.0022
10–20	SMT	1	$PR = -5.13 - 1.28WC + 4.48BD$	0.820	0.0322
		2	$PR = -1.72 - 2.07WC^2 + 1.39BD^2$	0.860	0.0322
		1,2,3	$PR = 129.09 - 4.00WC^3 - 174.91BD + 59.78BD^2$	0.979	0.0050
	NT	1,2	$PR = 12.30 - 46.38WC + 48.29WC^2$	0.871	0.0167
20–30	SMT	1,2	$PR = -1810.48 + 2219.14BD - 679.11BD^2$	0.856	0.0207
30–40	SMT	2	$PR = 3.19 - 9.11WC^2$	0.614	0.0370
		1,2,3	$PR = 2.41 + 31.18WC - 189.26WC^2 + 262.87WC^3$	0.942	0.0233
	NT	1	$PR = 3.60 - 4.29WC$	0.682	0.0221
40–50	SMT	1	$PR = 41.66 - 22.96BD$	0.805	0.0062
		1,2,3	$PR = -809.45 + 22.03WC - 191.45WC^2 + 356.53WC^3 + 1003.14BD - 309.00BD^2$	0.999	0.0273
	NT	1	$PR = 3.92 - 4.66WC$	0.918	0.0007

^aEquations are given for significant relationships. When use of squared or cubed terms did not improve the level of significance, those equations are not given.

^bTillage methods are: SMT, stubble mulch tillage; NT, no-tillage.

^cTerms are: 1, actual data values; 2, squared data value; 3, cubed data value.

^dCoefficient of determination.

^eSignificance level for coefficient of determination.

3.3. Penetration resistance–water content–bulk density relationships

Some obvious inverse relationships between PR and WC were noted and discussed in Section 3.2. In most cases, mean values for a given tillage method, cropping system, land condition, rotation phase, or crop were involved, but not enough data pairs were available for establishing a statistical relationship between PR and WC for a given situation. Sufficient data were available to establish relationships among PR, WC, and BD by combining results due to tillage and depth for various comparisons (CP-1, CP-2, and CP-3). (The CP-4 and CP-8 comparisons also involved tillage and depth, but were for the same conditions as for CP-1, CP-2, and CP-3). Soil BD was included because of its influence on PR (Taylor and Gardner, 1963; Vazquez et al., 1991). Equations resulting from the analyses are given in Table 4.

For combined data for all depths (0–50 cm) and both tillage methods, WC and BD accounted for only 0.534 (based on R^2 value) of the variation in PR. Prediction of PR from WC and BD for combined depths with SMT was considerably better than with NT when tillage methods were separated. Differences due to tillage method occurred also when separate analyses were made for individual depths.

With SMT, WC and BD terms were involved in most relationships pertaining to PR, both for combined data and individual depths. In contrast, WC and BD terms with NT were involved only for the combined depth data. For individual depths with NT, only soil WC was significantly related to PR. These results show that some soil strength factor largely independent of BD and affected by soil WC strongly influences PR of NT soil. No-tillage soils are not disturbed by tillage, and biopores created by soil organisms and root channels of preceding crops remain in place in such soils (Gantzer and Blake, 1978; Ehlers, 1982). It is, therefore, concluded that the biopores minimized effects of BD differences among different plots where NT was used and that the soils developed a 'rigid' structure independent of BD. Differences in BD for a given soil depth were as great or greater on NT as on SMT plots. The strength of such soils would be affected by WC, but not necessarily by BD, which apparently occurred in this study. Reports of improved trafficability on NT soils support this conclusion. For example, planting was possible under wetter soil conditions without problems with NT than with conventional tillage (Phillips and Young, 1973) and NT soil was accessible to heavy machinery sooner after rain than tilled soil (Baeumer and Bakermans, 1973). We also observed improved trafficability on NT fields, lending further support to the conclusion of a more rigid or stable soil structure with NT. While BD and PR generally were greater with NT than with SMT at 0–10 cm, wheat and sorghum grain yields with NT have equalled or exceeded those with SMT (Unger, 1994; Jones and Popham, 1997). We, therefore, further conclude that use of NT does not detrimentally affect the quality and production sustainability of soils similar to the one used in this dryland study.

Acknowledgements

The assistance of Larry J. Fulton, Biological Technician, in conducting this study and statistically analyzing the data is gratefully acknowledged.

References

- Allen, R.R., Fenster, C.R., 1986. Stubble-mulch equipment for soil and water conservation in the Great Plains. *J. Soil Water Conserv.* 41, 11–16.
- Baeumer, K., Bakermans, W.A.P., 1973. Zero-tillage. *Adv. Agron.* 25, 78–123.
- Ehlers, W., 1982. Penetrometer soil strength and root growth in tilled and untilled soil. *Proc. 9th Conf. ISTRO*. Osijek, Yugoslavia, pp. 458–463.
- Gantzer, C.J., Blake, G.R., 1978. Physical characteristics of Le Sueur clay loam soil following no-till and conventional tillage. *Agron. J.* 70, 853–857.
- Grant, C.A., Lafond, G.P., 1993. The effects of tillage systems and crop sequences on soil bulk density and penetration resistance on a clay soil in southern Saskatchewan. *Can. J. Soil Sci.* 73, 223–232.
- Greb, B.W., Smika, D.E., Black, A.L., 1967. Effect of straw-mulch rates on soil water storage during summer fallow in the Great Plains. *Soil Sci. Soc. Am. Proc.* 31, 556–559.
- Greb, B.W., Smika, D.E., Black, A.L., 1970. Water conservation with stubble mulch fallow. *J. Soil Water Conserv.* 25, 58–62.
- Hammel, J.E., 1989. Long-term tillage and crop rotation effects on bulk density and soil impedance in northern Idaho. *Soil Sci. Soc. Am. J.* 53, 1515–1519.
- Hill, R.L., Cruse, R.M., 1985. Tillage effects on bulk density and soil strength of two Mollisols. *Soil Sci. Soc. Am. J.* 49, 1270–1273.
- Jones, O.R., Popham, T.W., 1997. Cropping and tillage systems for grain production in the Southern High Plains. *Agron. J.* 89, 222–232.
- McCalla, T.M., Army, T.J., 1961. Stubble mulch farming. *Adv. Agron.* 13, 125–196.
- Norwood, C., 1992. Tillage and cropping system effects on winter wheat and grain sorghum. *J. Prod. Agric.* 5, 120–126.
- Norwood, C., 1994. Profile water distribution and grain yield as affected by cropping system and tillage. *Agron. J.* 86, 558–563.
- Phillips, S.H., Young, Jr., H.M., 1973. No-Tillage Farming. Reiman Associates, Milwaukee, WI, 224 pp.
- Statistical Analysis Systems, 1989. SAS/STAT User's Guide. Version 6, 4th edn., vol. 2. SAS, Cary, NC.
- Steyn, J.T., Tolmay, J.P.C., Human, J.J., Kilian, W.H., 1995. The effects of tillage systems on soil bulk density and penetrometer resistance of a sandy clay loam soil. *S. Afr. J. Plant Sci.* 12, 86–90.
- Taylor, H.M., Gardner, H.R., 1963. Penetration of cotton seedling taproots as influenced by bulk density, moisture content, and strength of soil. *Soil Sci.* 96, 153–156.
- Unger, P.W., 1978. Straw-mulch rate effect on soil water storage and sorghum yield. *Soil Sci. Soc. Am. J.* 42, 486–491.
- Unger, P.W., 1984a. Tillage and residue effects on wheat, sorghum, and sunflower grown in rotation. *Soil Sci. Soc. Am. J.* 48, 885–891.
- Unger, P.W., 1984b. Tillage effects on surface soil physical conditions and sorghum emergence. *Soil Sci. Soc. Am. J.* 48, 1423–1432.
- Unger, P.W., 1994. Tillage effects on dryland wheat and sorghum production in the southern Great Plains. *Agron. J.* 86, 310–314.
- Unger, P.W., Fulton, L.J., 1990. Conventional- and no-tillage effects on upper root zone soil conditions. *Soil Tillage Res.* 16, 337–344.
- Unger, P.W., Pringle, F.B., 1981. Pullman soils: distribution, importance, variability and management. *Bull. B-1372*, Texas Agric. Exp. Stn., College Station, TX.
- Unger, P.W., Wiese, A.F., 1979. Managing irrigated winter wheat residues for water storage and subsequent dryland grain sorghum production. *Soil Sci. Soc. Am. J.* 43, 582–588.
- Vazquez, L., Myhre, D.L., Hanlon, E.A., Gallaher, R.N., 1991. Soil penetrometer resistance and bulk density relationships after long-term no tillage. *Commun. Soil Sci. Plant Anal.* 22 (19/20), 2101–2117.